Proceedings of the Institute of Acoustics

MEASUREMENT OF THE THICKNESS OF CONCRETE STRUCTURES USING WAVE PROPAGATION TECHNIQUES

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1. INTRODUCTION

The examination of civil engineering structures for either quality control or damage/integrity inspection requires the use of non-destructive testing techniques which are reliable, accurate and easy to apply [1]. One technique is to excite a "thickness resonance" in the structure [2]. This may be considered to be the first longitudinal mode across the thickness of the structure. If the first mode occurs when the thickness equals half a wavelength, then thickness, t, = c/2f, where c is the longitudinal wave speed in the material and f is the first observed resonance frequency in Hz. Obviously some knowledge of the material properties must be obtained before inspection of a structure can occur. In real structures, many different wave types propagate, and for the technique to be accurate the correct through-thickness resonance must be identified from the measured data. Detailed is a series of experiments on a concrete beam of varying thickness. These experiments highlight the problem of identifying the desired resonance frequency and offer some solutions to the problem. Also described is the instrumentation which was refined over the testing period.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic diagram of the transducer configuration that was used on the concrete beams. It consisted of a force washer (transducer) mounted on an aluminium disc. As the centre of the force washer was hollow, a 3 g accelerometer was placed in the middle of the disc. It was necessary to recess a hole in the disc to take the accelerometer and to prevent unnecessary strain of the accelerometer cable. A plate with an attachment to take an electrodynamic shaker was attached to the top of the force washer using grease.

The whole transducer system was attached to a concrete beam using hot melt glue. This adhesive was found to have the duel properties of good adherence, but simple to remove. As many positions on the structure were to be measured, it was necessary to be able to remove the instrumentation quickly and easily. It was possible to excite the system using a steady state sinusoidal signal. The response of the system was monitored using the force washer and the accelerometer. A phase meter was attached between the transducer outputs, which were also connected to vibration meters.

Three configurations of concrete beam were used in the testing (Figure 2). The first configuration consisted of a single beam (beam 1) resting on cork blocks. Beam 1 had dimensions 10 × 10 × 300 cm. The second beam configuration consisted of beam 1 with beam 2 stuck to it using epoxy putty. Beam 2 had the same cross-section as beam 1 but was only 1 m long. It was stuck in the middle of beam 1. Beam 3 had the dimensions 10 × 4.6 × 100 cm and was stuck, again using epoxy putty, to beam 1. This was the third beam configuration. Thus, the third configuration consisted of three beams and three different thicknesses of cross-section. It should be noted that small reinforcement rods ran through the lengths of all of the beams.

3. TESTS ON A UNIFORM CONCRETE BEAM

Beam 1 was excited using steady state sinusoidal excitation. The resonance frequencies of the beam were detected using the transducer configuration. Initially the excitation was applied at the centre of the beam. The first and third mode shapes of the beam were measured. From these, it was determined that the beam behaved as a uniform free-free structure.

The transducer configuration was placed at different positions on the beam and resonance frequencies were detected. Figure 3 shows the various frequencies detected at different positions. The frequency limit on testing was 20 kHz which was the upper frequency limit of the instrumentation. From impacting the end of the beam, an estimate of the longitudinal wave speed in the rod was obtained. This gave c_l = 3545 m/s.

The measured transfer inertance (frequency domain ratio of acceleration to force) of the beam is shown in Figure 4. It was reasonable to assume that the observed resonances were associated with longitudinal modes of the beam. These modes would be ene to ene of the beam and not through the thickness, as the beam was impacted on the end. The frequencies are also shown in Figure 3. Assuming that the beam behaved as a free-free longitudinal rod and that 700 Hz was its first natural frequency, then the wave speed, c_l, would be 3841 m/s.

Averaging the two wave speeds gives c_l = 3693 m/s. If this is the true wave speed, then the first "thickness resonance" would be 18174 Hz. A resonance at 18.5 kHz was observed at position 1. At the other four positions, a resonance was observed at 14.5 kHz, which would indicate a wave speed of 2946 m/s. It may be that a wave speed measured end-to-end would be higher than a "cross-thickness" wave speed due to the presence of the reinforcement bars. Thus, it is uncertain whether the thickness resonance was observed at 14.5 kHz or 18.5 kHz.

4. TESTS ON BEAM CONFIGURATION TWO

Resonance frequencies were measured on the second beam configuration. Figure 5 shows the frequencies observed on the single and double layers. The division between the single and double layers is shown. To determine which resonance frequencies were due to longitudinal waves and which were due to flexural waves another accelerometer was mounted on the beam directly under the excitation point. If the mode of vibration was purely flexural, the difference of the accelerometer outputs would be zero and if the mode was purely longitudinal the sum of the outputs would be zero. Thus, by comparing the sum and difference of the two accelerometer outputs it was possible to establish if the mode of vibration was predominantly flexural or longitudinal. Figure 6 shows the observed modes for positions on the beam. On the single layer part of the structure, only one longitudinal mode was observed, whereas on the double layer section, two longitudinal modes were observed. It should be noted that the higher longitudinal modes at positions 22, 32 and 33 (double layer) were at the same frequency as the longitudinal mode of the single layer. This implies a "thickness resonance" in one of the regions of the double layer section.

Thus, if the "thickness resonance" was 15.3 kHz, the wave speed would be 3100 m/s. This is lower than the wave speed measured on the single beam, confirming that the reinforcing rods affect the "end-to-end" wave speed of the beam. Similarly, the average wave speed determined from the first "thickness resonance" on the double layer was 3240 m/s.

5. TESTS ON BEAM CONFIGURATION THREE

The purpose of the third beam configuration was to have a double layer section where the layers were of different thickness. This was to prevent the "thickness resonance" of the double layer being a multiple of the "thickness resonances" of the single layer. Figure 7 shows the observed resonances on the double layer region of 10 cm beam over 4.6 cm beam. It may be observed that two thickness resonances were recorded for this region. The resonances are not multiples of each other.

Assuming $c = 3100$ m/s and $c = f\lambda$, one obtains the following values.

Position	Thickness Measured	Predicted from Thickness Resonance	Error
13	0.1460 m	0.1218 m	- 17%
13	0.1016 m	0.1003 m	- 1%
14	0.1460 m	0.1446 m	- 1%
14	0.1016 m	0.1019 m	1%

6. CONCLUSIONS

The transducer configuration was used to measure "thickness resonances" on various concrete beam configurations. A transducer mounted under the excitation point was used to determine if wave motion was flexural or longitudinal in nature. "Thickness resonances" were measured on all three beam configurations. It was found that it was possible to distinguish between flexural and longitudinal modes of the beam configurations. By determining the different response modes it was possible to confirm the detection of "thickness resonances". Obviously the technique of mounting transducers on either side of the structure limits the technique. It may be possible to distinguish the different modes from one side only by utilising the difference in wavelength.

7. REFERENCES

[1] J KRAUT KRAMER & H KRAUT KRAMER, 'Ultrasonic Testing of Materials', Springer-Verlag (1983).

[2] W N REYNOLDS, S J WILKINSON & D C SPOONER, 'Ultrasonic Wave Velocities in Concrete', Magazine of Concrete Research 30, pp 139-144 (1978).

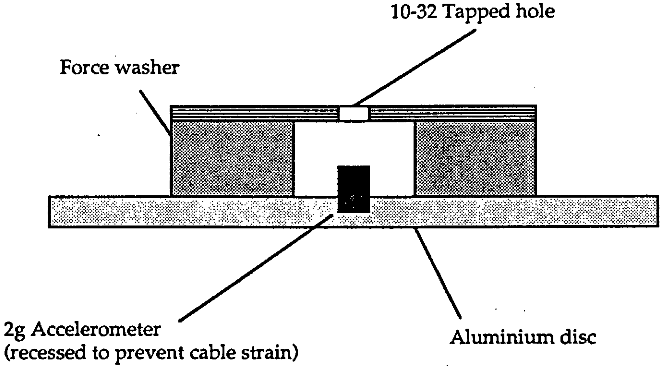

Figure 1: Transducer arrangement.

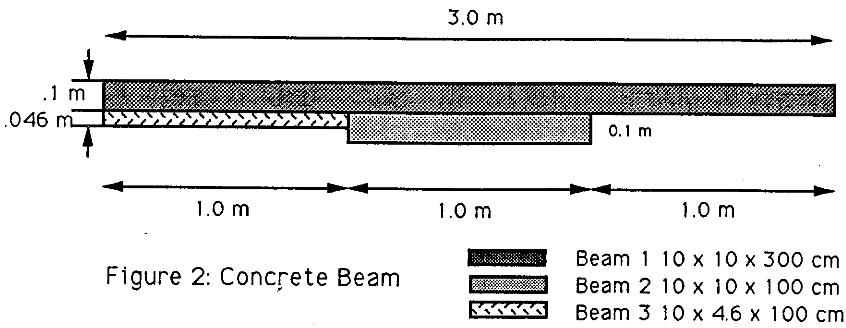

Figure 2: Concrete Beam

52 measuring points equally spaced on beam

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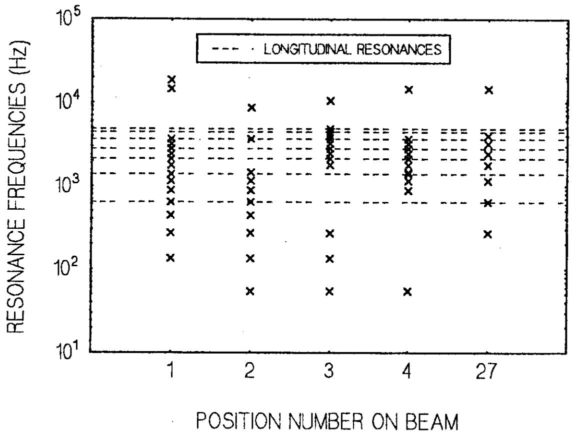
FIGURE 3:OBSERVED RESONANCES FOR BEAM CONFIGURATION 1



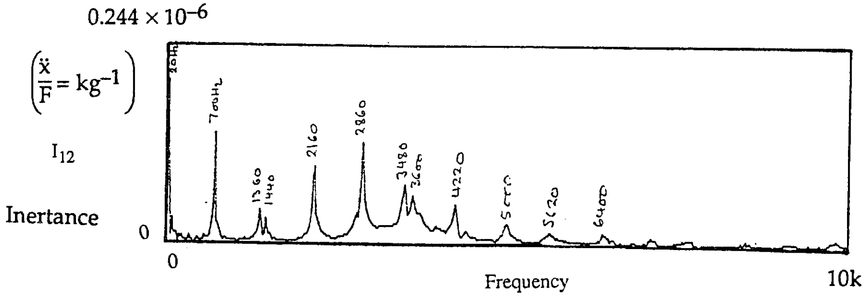


Figure 4: Transfer function end to end for longitudinal motion.

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FIGURE 5:OBSERVED RESONANCES ON BEAM CONFIGURATION 2.

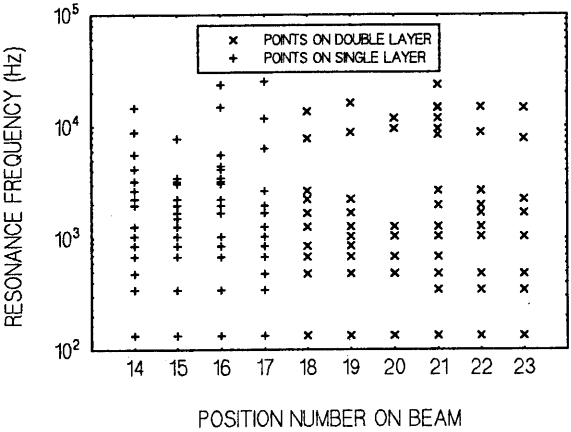

FIGURE 6:OBSERVED RESONANCES ON BEAM CONFIGURATION 2.

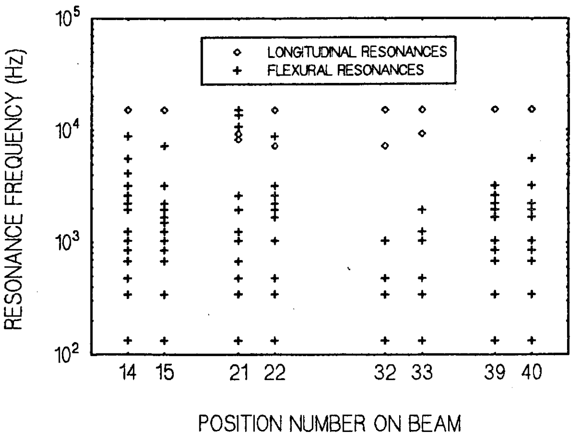

FIGURE 7: OBSERVED RESONANCES ON BEAM CONFIGURATION 3.